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XIX.

ON THE THERMAL CONDUCTIVITY OF CAST IRON AND OF CAST NICKEL.

By EDWIN H. HALL.

Presented June 15, 1892.

IN the year 1890, having occasion to construct a thermopile of nickel and cast-iron, for experiments upon cylinder condensation in steam-engines, I wished to know approximately the ratio of the thermal conductivities of these two metals. To my surprise, I could find nothing in the books examined concerning the thermal conductivity of nickel. As to the same property in iron there was considerable information in print, but different experimenters had found very different values. I therefore determined to seek the information which I needed by experiment, following the well known method of Forbes and of Tait, — a study of the permanent gradient of temperature along a bar heated at one end, in a room of constant temperature, and of independent observations on the rate of heat emission from a bar of the same material in the same room. Forbes and Tait both used a shorter bar for the emission experiments than for the steady flow. I used the same bar for both parts of the work. My results, though claiming no great accuracy, are of some interest to the scientific world, as giving an approximate value for the thermal conductivity of nickel and of cast-iron.

I had two bars of cast-iron made, each, when finished and thinly nickel-plated to prevent rusting, about 92 cm. long and 2.52 or 2.53 cm. in width and thickness. One was of ordinary Southern cast-iron, brittle in quality, specific gravity 7.06; the other was of so called gun-iron, specific gravity 7.18, which is very much tougher than ordinary cast-iron. A number of castings were made for the gun-iron bar before one was obtained that was reasonably free from blow-holes. No such difficulty was experienced with the other iron.

To procure a nickel bar as large as the iron ones gave no small trouble. It was not to be found in the market, but some 23 lb. of commercial nickel, in various shapes, put into a new melting-pot by an obliging brass-founder, yielded, after one or two failures, a casting from which a bar 91.5 cm. long and about 2.55 cm. in width and thickness was worked out. The high melting point of nickel makes it a difficult metal to cast in the form of a long bar. A baked sand mould was finally used, and one end of it was elevated considerably above the other, in order that the whole might become filled before the metal cooled. Even with this device the success attained was not perfect, and the finished nickel bar was marred by many flaws. A little experience, however, shows that a blow-hole may be of considerable size without deserving to be counted among the more serious causes of error in the determination of thermal conductivity. Borings or cuttings from this nickel bar were analyzed by a chemist, and were found to contain *several per cent* of iron, and small quantities of other impurities, of which silicon was one. All of the nickel put into the melting-pot was represented when purchased to be fairly pure, but it was discovered too late that two pounds of it was of very poor quality, that is, contained much iron.

In each of the three bars holes about 0.55 cm. wide and about 2.3 cm. deep were bored to receive the thermometer bulbs. The length of each bar was divided into nine nearly equal parts, and one hole was bored at the middle of each part, so that the holes were a little more than 10 cm. distant from one another. Each hole was partly filled with mercury.

The thermometers used with the bars had bulbs about 0.45 cm. wide and about 2.0 cm. long. They were graduated for the purposes of this investigation on the basis of bulb-immersion only. They were not high grade instruments, and some of them were probably in error nearly $0^{\circ}.5$ at various points between 0° and 100° . At 100° they read from $0^{\circ}.1$ to $0^{\circ}.3$ or $0^{\circ}.4$ low. Above 100° the errors were more serious, — thermometer no. 8, which was sometimes used with a reading of 150° or higher, having an error of about 2° at that temperature, according to the comparison afterward made with a good thermometer lent me by Professor Holman of the Massachusetts Institute of Technology.

The conduction experiments were made in May and June, 1890, in the north side of the middle basement of the Jefferson Physical Laboratory. The bars were supported near their ends on thin

wooden pillars, about 20 cm. above the top of a long wooden table. For the steady flow experiments two bars were placed in line with their ends nearly touching, and both were heated at once by the same Bunsen flame, which was protected from drafts of air by a tin casing about 38 cm. tall and 13 cm. square, pierced on two sides to admit the ends of the bars. The general temperature of the room was observed by means of six ordinary Centigrade thermometers, of which one was placed on the table near the heated bar, one about 1.25 cm. above the middle of the bar and about 30 cm. from the ceiling of the room, one near the north wall about 2.5 m. distant, another about equally distant upon a south wall, another some 10 m. away upon the western wall, and another about the same distance toward the east. During the experiments on steady flow and on rate of cooling, the thermometer lying on the table usually read about $0^{\circ}.5$, and the one hanging above the bar about 2° , higher than the mean of the six. The mean reading of these six thermometers differed from the mean reading of the eight thermometers used on the bars less than $0^{\circ}.1$, when all were placed together in water near 20° . The mean reading of the six *room* thermometers during the actual experiments upon the bars usually varied only a few tenths of a degree in an hour.

Not wishing to devote a great deal of time to the work in hand, I was content with a rather rough approximation to a state of steady flow of heat. The method followed was to take several rapid observations of all the bar thermometers at five-minute intervals, after they had become reasonably constant. Upon the basis of such observations calculation was easily made of the rate at which heat was *accumulating* in the bar at any given instant. In some cases this accumulation made a difference of several per cent in the amount of heat entering into the calculation of the conductivity. As an example of the method of observation, the following series made with the nickel bar will serve, the columns headed 1, 2, 3, etc., being readings of the thermometers no. 1, no. 2, no. 3, etc.:—

Time	1.	2.	3.	4.	5.	6.	7.	8.
	°	°	°	°	°	°	°	°
12:48	27.4	29.0	32.2	37.7	47.8	63.9	93.5	144.6
12:53	27.5	29.0	32.4	37.9	47.9	63.9	93.2	144.0
12:58	27.6	29.2	32.4	37.9	47.9	63.8	93.1	143.7
1:03	27.7	29.3	32.4	37.9	47.8	63.7	92.7	143.0

From these observations the following *estimate* may be made:—

Time	1.	2.	3.	4.	5.	6.	7.	8.
	°	°	°	°	°	°	°	°
12:50½	27.45	29.00	32.30	37.80	47.85	63.90	93.35	144.30
1:00½	27.65	29.25	32.40	37.90	47.85	63.75	92.90	143.35
Means	27.55	29.13	32.35	37.85	47.85	63.83	93.13	143.83
Rise in 10 minutes	.20	.25	.10	.10	.00	—15	—45	—95

This was an unusually bad case.

Each bar was tested twice in a condition of approximate steady flow, that end which was heated in one test being the cool end in the other test. This trial of both ends in turn was probably suggested by the fact that the ends of the nickel bar were somewhat different in appearance, owing to that too rapid cooling of the molten metal which has already been mentioned.

For determining the rate of emission of heat each bar was twice heated and cooled as a whole. As only eight thermometers were available for this purpose, the middle hole was left unoccupied in all the rate-of-cooling experiments. The order of experiments was as follows:—

Cast Gun-Iron.	Southern Cast-Iron	Nickel.
May 30, rate of cooling.	May 31, rate of cooling.	June 10, rate of cooling.
June 2, steady flow.	June 2, steady flow.	“ 11, steady flow.
“ 7, rate of cooling.	“ 4, rate of cooling.	“ 11, “ “
“ 11, steady flow.	“ 11, steady flow.	“ 12, rate of cooling.

The bars were generally, if not in all cases, rubbed somewhat to brighten their surfaces just before being used. In experiments on the rate of cooling the whole length of the bar was first heated to about 115° or 120°, and as it cooled observations of all the thermometers upon it were made at regular intervals, — two-minute intervals at first and longer ones afterward, — until the bar was perhaps not more than 15° (in the earlier cases about 20° and in the later about 10°) above the general temperature of the room. The accordance of the two sets of cooling observations made with each bar was, on the whole, very satisfactory. From each set a curve was plotted. The following values taken from these curves will show how close the agreement was:—

Cast Gun-Iron.	Temp above that of Room.	Cooling per Second.
	°	°
May 30	30	.0098+
"	50	.0178+
"	80	.0300
June 7	30	.0102—
"	50	.0178—
"	80	.0300
Southern Cast-Iron.		
May 31	30	.0102—
"	50	.0178+
"	80	.0303—
June 4	30	.0100
"	50	.0182—
"	80	.0303+
Nickel.		
June 10	30	.0098—
"	50	.0178—
"	80	.0306—
June 12	30	.0100
"	50	.0178+
"	80	.0311—

In order that the air currents in the neighborhood of the bar during the cooling experiments might be, as nearly as practicable, like those prevailing during the steady flow observations, the Bunsen lamp within the tin protecting case already described was kept burning near one end of the cooling bar, the flame being of about the same height in all cases. A screen was placed between the box and the end of the bar to prevent direct radiation.

No attempt was made to represent by equations the temperature of the different parts of the bars during the condition of steady flow. The observations for every case were merely plotted carefully, with distances along the bars for abscissæ, and with temperatures, minus temperature of the room, for ordinates. Through the tops of the ordinates a smooth curve was drawn. The gradient of temperature at any point of the bar was found by measurement of the inclination of the curve at that point. The mean temperature of each division of the bar whose surface emission had to be considered was easily estimated from the mean height of the curve for that division. The amount of heat emitted from each such division was then estimated by reference to the curves, already mentioned, showing rate of cooling as a function of temperature of metal *minus* temperature of room. Wherever the specific heat of

iron or of nickel appeared in the calculations, Naccari (*Atti della R. Accademia delle Scienze di Torino*, Vol. XXIII., 1887) was followed as an authority. He gives these values:—

	Sp. ht. of Iron.	Sp. ht. of Nickel.
At 15° C.	0.1091	0.1057
At 50°	0.1113	0.1090
At 100°	0.1151	0.1137
At 150°	0.1196	0.1185

As any curve drawn, even when it runs smoothly and accurately through the points given by observation, may not represent the exact condition of things at intermediate points, and as there is liability to considerable error in determining the gradient of a line the curvature of which is everywhere changing, the conductivity was calculated for two points upon each curve of steady flow, both points lying between the two thermometers nearest the heated end of the bar. The difference between the two values thus found from any one curve is not to be explained by variation of conductivity with temperature. It is due, in the main, to errors of experiment or calculation. As there are two calculated values of conductivity from each curve of steady flow, and two such curves for each bar, there are four calculations of conductivity for each bar, but no two of these four are entirely independent, for the two sets of observations on the rate of cooling of each bar were combined for use with each curve of steady flow in that bar. The results are here presented:—

SOUTHERN CAST-IRON.

	Conductivity (c. g. s.).		Temperature.	
End no. 1 heated,	.1102	} .1158	at 119° C.	} 112.5
June 2, 1890	.1214		106	
End no. 2 heated,	.0987	} .0981	123	} 116.5
June 11, 1890	.0975		110	
Mean	.107			114

CAST GUN-IRON.

	Conductivity (c. g. s.).		Temperature.	
End no. 1 heated,	.1049	} .1045	at 116° C.	} 110.5
June 2, 1890	.1042		105	
End no. 2 heated,	.1011	} .1036	121	} 115.0
June 11, 1890	.1062		109	
Mean	.104			113

IMPURE CAST NICKEL.

	Conductivity (c. g. s.)		Temperature.	
End no. 1 heated,	.108	} .1065	at 127° C.	} 116
June 11, 1890	.105		" 115	
End no. 2 heated,	.1030	} .1062	" 128	} 117
June 11, 1890	.1095		" 116	
Mean	.106			116

The avowedly rough and hasty character of the experiments being considered, the agreement of the results obtained in the case of gun-iron and in the case of nickel is entirely satisfactory. In the case of the other bar, the results do not agree among themselves so well as one could wish, although, in view of the acknowledged difficulty which attends experiments upon thermal conductivity, they should not be considered surprisingly discordant. I can offer no explanation of the fact that both the largest and the smallest calculated values of the conductivity were obtained from this bar. The mean value, it will be observed, is not very far from the mean obtained with the gun-iron bar. The mean value for each of the iron bars is, I believe, smaller than any other investigator has recorded for iron, though not smaller than has been found for Bessemer steel.

The following values are taken from Landolt and Börnstein's *Physikalisch-Chemische Tabellen* : —

	Temperature.	Conductivity.	Observer.
Iron	100° C.	.1417	Angström.
"	0	.1988	"
"	100	.1627	Lorenz.
"	0	.1665	"
Wrought-Iron	100	.1567	Forbes.
" "	0	.2070	"
Bessemer Steel	15	.0964	Kirchhoff and Hanseemann.

According to Kirchhoff and Hanseemann (*Wied. Annalen*, Vol. IX. p. 5), the conductivity of iron (in c. g. s. units) is expressed by the formula $.1694 - .00034 (t - 15)$.

This gives for 15° C. the value .1694,
and for 100° C. the value .1405.

The iron used by Lorenz had the density 7.828 (*Wied. Annalen*, Vol. XIII. p. 438), and was therefore not cast-iron. That used by

Kirchhoff and Hansemann (*Wied. Annalen*, Vol. IX. p. 6) contained only 0.129 per cent of carbon, and was therefore not cast-iron. I have as yet found no description of the iron used by Angström, but it is probable that he too used a tolerably pure specimen. Reviewing the course of my experiments, I find no reason for supposing my values to be, as a whole, much too low. The very great interval of temperature, about 50° , between thermometers 8 and 7, next the heated end of the bars, was no doubt too great for the greatest precision of results, but a number of calculations of the conductivity for points between thermometers 7 and 6 give a mean very near those found for points between 8 and 7. The natural conclusion is, that cast-iron has a much smaller conductivity than wrought-iron.

But whatever may be the value of my results as to iron alone, there can be little doubt that the main object for which the experiments were made, namely, to determine approximately the relative conductivity of cast iron and cast nickel, has been attained. The thermal conductivity of the nickel here used is very nearly the same as that of the cast-iron bars with which it was compared.

In spite of the very considerable amount of laborious study that has been devoted to the thermal conductivity of iron, authorities differ widely in their conclusions, especially upon this particular, the change of conductivity with change of temperature, as the numbers above given show. This difference comes in part from different opinions as to the change of specific heat of iron with change of temperature. The work of a number of investigators within the past ten years has added greatly to our knowledge upon this latter subject, and possibly recalculations of thermal conductivity from old observations might now be made with advantage.

I hope soon to make trial of a method for estimating thermal conductivity somewhat different from any heretofore used.

January 7, 1893.

I have recently, with the help of students, made additional observations upon steady flow and the rate of cooling in the Southern cast-iron bar, placed now in the main lecture-room of the Physical Laboratory. The new observations on rate of cooling extended about 46° only,—from $+110^{\circ}$ to $+64^{\circ}$; but for this range they indicated a rate about 10% greater than was found in the basement in 1890. A rough calculation from this new study of the bar indicates for end no. 1 a conductivity practically the same as

that found for this end before; but for end no. 2, a conductivity about 6% greater than previous observations showed.

Chemical analysis of borings from the nickel bar showed the following composition:—

Nickel		85.44%
Iron		7.56
Silicon		0.42

with small quantities of antimony, arsenic, copper, manganese, phosphorus, sulphur, and tin.

Analysis of borings from the gun-iron bar showed:—

Carbon (total)		3.64%
Phosphorus		0.59
Silicon		1.33